LIGHT TRAPPING ENHANCEMENT FOR THIN-FILM SILICON SOLAR CELLS BY ROUGHNESS IMPROVEMENT OF THE ZNO FRONT TCO

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ABSTRACT : This paper presents a study on the effect of the surface roughness of front TCO layers on the amorphous silicon solar cell performance. The same amorphous p-i-n silicon solar cell was deposited on four front ZnO substrates with different surface roughnesses. Starting from a flat sputtered ZnO layer and ending at an etched rough ZnO deposited by the Low Pressure Chemical Vapor Deposition process, the haze factor of these layers was progressively increased. The analysis of the spectral response of the solar cells shows that the haze factor alone of the front TCO layer is not sufficient to characterize fully its influence to the light trapping of an amorphous silicon solar cell. The structure of the TCO surface has to be taken into account, as the latter will directly influence the topology of the amorphous solar cell deposited on this layer and additionally affect the light trapping potential in the cell.
Keywords: TCO Transparent Conducting Oxides - 1; ZnO - 2; Light Scattering - 3.

1. INTRODUCTION

The main properties that TCO (Transparent Conductive Oxyde) layers for solar cells generally need to possess are high values of both transparency and conductivity. However, for silicon thin-film solar cells, the TCO layer must also act as a light scatterer, in order to increase the effective light path in the solar cell and, thus, to enhance the overall absorption. In other words, for a given value of the absorption, the cell thickness can be decreased. In case of amorphous silicon (a-Si:H) solar cells, a thickness reduction leads, furthermore, to a decrease in the detrimental effects of light-induced degradation of the cell efficiency. In case of microcrystalline solar cells, for which deposition rates are generally low, the reduction of cell thickness allows one to decrease the deposition time of the cells, and, thus, to lower fabrication costs.

Light scattering depends mainly on the surface roughness of layers [1,2]. Therefore, it is indispensable for applications in thin-film silicon solar cells to optimize the surface roughness of the TCO layers, in order to enhance the light scattering into the solar cell. In this paper, we focus on the surface roughness of the front TCO of p-i-n configured a-Si:H solar cells. This layer is the one through which the light enters the solar cell. It applies its scattering action to the whole incoming light, and its surface roughness needs to be suitable to diffuse especially the red light. Furthermore, in the p-i-n configuration, the front TCO is the first layer deposited in the fabrication process. Therefore, its surface roughness will have an influence on the surface roughness of layers deposited hereafter, i.e. on the whole p-i-n solar cell. This, in its turn, will contribute to enhance further the light scattering within the solar cell.

The purpose of this paper is to investigate what is important w.r.t. surface roughness of the front-TCO in order to be able to effectively enhance light trapping within p-i-n a-Si:H solar cells. For this study, we observed the influence of front TCO with different haze factors and surface morphologies on the p-i-n solar cell spectral current generation.

2. EXPERIMENTAL

2.1 Front TCO

The TCO we have used here is Al-doped and B-doped ZnO. Apart from the fact that this material has good optical and electrical properties (transparency > 80%, square resistance < 5 Ω_{sq}), it is also stable w.r.t. hydrogen plasmas (unlike SnO_2) [3]. This is a significant advantage, because hydrogen dilution is currently used to deposit thin-film silicon solar cells by Glow Discharge (GD) methods (here Very High Frequency (VHF) – GD).

Our goal was to have four ZnO layers with comparable optical transmission and electrical properties, but with four different surface roughnesses. We used two types of ZnO deposition processes : sputtering and Low Pressure Chemical Vapor Deposition (LPCVD). Furthermore, for half of the ZnO layers obtained by those two deposition processes, we additionally enhanced the surface roughness by a post-etching process [4].

We characterized the ZnO layers by Atomic Force Microscopy measurements to determine the Root Mean Square (RMS) value of the surface roughness. In the visible wavelength range the values of total and diffuse transmission were measured by a spectrometer to obtain the haze factor. This latter value is calculated as the ratio of diffuse transmission to total transmission at 600 nm. The haze factor is, like the RMS value, an indication for the light scattering capability of the TCO layer. We used the four-probe method to measure the resistance of the TCO layers, and carried out Scanning Electron Microscopy (SEM) observations on their surface.

2.1.1 ZnO by sputtering

To deposit sputtered ZnO layers, we used a ZnO:Al target and a Radio Frequency (13.56 MHz) plasma at room temperature. The typical thickness of these sputtered layers used is 1.5 µm. The RMS roughness value of such a surface is about 6 nm, and the haze factor is only 0.4%. These values are very low, as expected for a flat surface.

To enhance the surface roughness of this sputtered ZnO layer without altering its electrical and optical properties, we applied a post-etching method, already used in previous works [4]. For an etching-time of 9s with a 5‰ diluted HCl

solution, we measured a RMS roughness value of about 21 nm and a haze factor of 14.6%. These values are slightly higher than those of the flat sputtered ZnO. However, they are not the highest values that can be obtained by this post-etching treatment. A longer etching time would indeed lead to a higher RMS roughness value and to a higher haze. In fact, in order to obtain silicon solar cells with high efficiencies, the Jülich group applies a longer etching time to their sputtered ZnO, obtaining, thus, rougher front ZnO layers [5]. But in our case, we wanted to increase progressively the haze of our four ZnO layers. Therefore, we just etched the sputtered ZnO layer a little bit in order to obtain a haze factor between a flat ZnO layer, and an unetched LPCVD ZnO layer (see next paragraph).

2.1.2 ZnO by LPCVD

By the oxydation of Diethylzinc (DEZ) and the use of Diboran as doping gas, at a temperature range of 150°C<T<200°C, we obtain by LPCVD a ZnO suitable for TCO applications. The typical thickness is 2.6 μm. These ZnO layers show a RMS roughness of about 60 nm and a haze factor value of 22.8%.

To enhance again the surface roughness of a LPCVD ZnO layer, we applied also a post-etching treatment here. We increased the etching time to 85s, in order to obtain a highly rough surface. However, solar cells deposited on this kind of strongly rough substrate were all shunted. Therefore, we deposited after this hard post-etching treatment an additional thin layer of LPCVD ZnO. We finally obtained thereby a ZnO layer with a surface quite similar to the one of the as-grown LPCVD ZnO, but with a RMS value of about 80nm, and a haze factor of 41%.

These four ZnO layers reveal a relatively constant value of the surface resistance of about 5 Ω_{sq} ± 0.5 and a total optical transmission of around 80% in the spectral range of 400 nm to 800 nm. In all cases AF45 glasses from Schott were used as substrates. Fig. 1 shows the total and diffuse transmissions of those four ZnO layers.

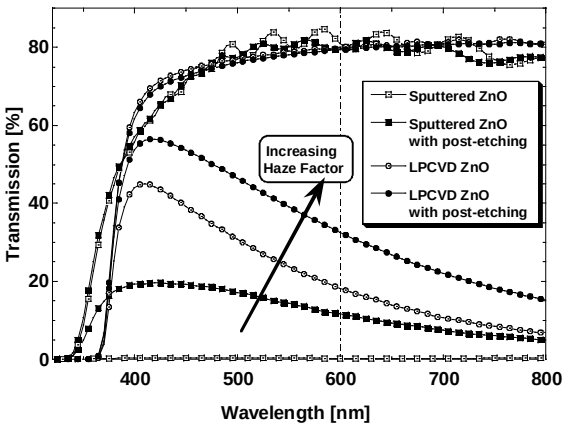

Fig. 1: Total and diffuse transmission of our four ZnO layers having different surface roughnesses.

One can effectively observe the regular variation of the diffuse transmission and, therefore, the progressive increase of the haze factor.

2.2 p-i-n amorphous silicon solar cells

On these four ZnO layers identical p-i-n a-Si:H solar cells were deposited by the Very High Frequency Glow Discharge (VHF-GD) method [6] : the amorphous i-layer thickness was kept around 3500Å-4000Å. The back contact consists of a ZnO layer. As only the effect of the surface roughness of the front TCO was of interest, we did not try to optimize the <p> and <n> thicknesses of the solar cells for each substrate. That means we deposited a layer of amorphous silicon thick enough (in all cases) to avoid shunting effects by pin-holes. We did not specially care if the p-layer was too thick, since only the red wavelength response was of interest. Furthermore, in order to observe only the bare effect of the front TCO surface, we did not deposit a back reflector (e.g. Silver), but only a ZnO back contact layer. The open circuit voltage (V_{oc}) and the fill factor (FF) of these solar cells were measured under AM1.5 illumination. The trend of the spectral response (SR) curves (normalized w.r.t. their maximum values) were compared in the red wavelength range. Finally, additionally to Scanning Electron Microscopy (SEM) pictures of the naked ZnO layers, we performed SEM observations on the n-layers, in order to look at the surface features of the cells deposited on different ZnO layers.

3. RESULTS AND DISCUSSION

3.1 Results on p-i-n amorphous solar cells

The solar cells deposited on our four kinds of front ZnO layers show V_{oc} values all between 0.87 V and 0.89 V and FF values between 72% and 74%. These excellent values indicate the high performance of all cells studied here. However, significant variations were observed in the SR curves. Fig. 2 shows the trends of the four SR curves in the red-wavelength region.

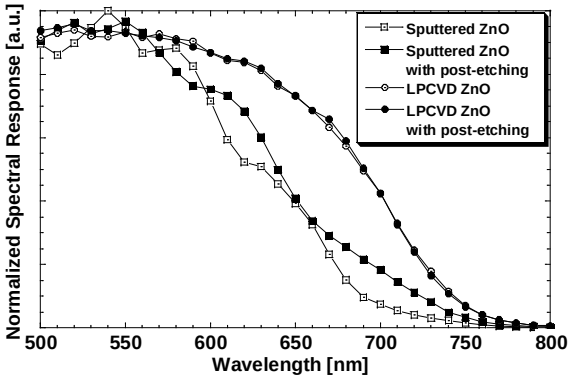

Fig. 2: Spectral response of p-i-n a-Si:H solar cells deposited on the four different front ZnO layers of Fig.1.

We observe a strong difference between solar cells deposited on LPCVD ZnO and these deposited on sputtered ZnO. Furthermore, in the case of sputtered ZnO, we observe an increase in the SR for the post-etched sputtered ZnO substrate. This effect is due to the better light scattering induced by the roughening of the front ZnO compared to flat sputtered ZnO. Surprisingly, in the case of LPCVD ZnO, one cannot observe any difference between both SR curves; the SR of the solar cells deposited on a rough as-grown LPCVD ZnO layer and on an “even more

rough" post-etched LPCVD ZnO layer are identical. Furthermore, when we deposit a reflector on the latter cells, there is a further increase of the current in the red-wavelength region of both SR curves. This means that both cells are not in the case of "optical saturation", where all the light is absorbed before reaching the end of the solar cell. Therefore, the effect of "optical saturation" cannot explain the similarity between the two SR curves of the solar cells deposited on the two different LPCVD ZnO substrates.

3.2 Comparison between SR and haze factor

In Fig. 3 the haze factor values at 600nm of our four different front ZnO layers, and the SR values at 600 nm of the solar cells deposited on these front ZnO layers are represented.

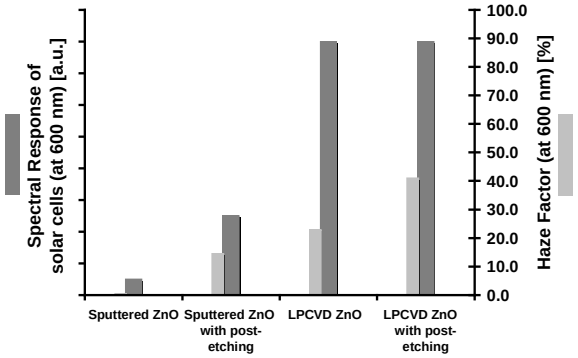

Fig. 3: Haze factors (at 600nm) of the ZnO layers possessing different surface roughness, and corresponding spectral response values (at 600 nm) of p-i-n a-Si:H solar cells deposited on these ZnO layers.

Surprisingly, a close correlation between these two parameters cannot be found. Moreover, the considerably improved SR of the solar cell deposited on the LPCVD ZnO, as compared to sputtered ZnO, seems not at all be explainable with the haze alone. Therefore, it was of interest to analyze the surface topology of the different ZnO substrates and the solar cells deposited on them.

3.3 Surface texture of the front ZnO and the a-Si:H solar cells

Figs. 4a and 4b show SEM pictures of the sputtered ZnO layer (a) and the n-layer of the p-i-n solar cell deposited on it (b).

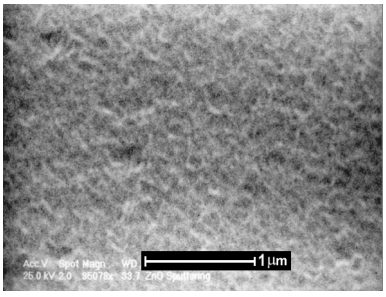

Fig. 4a: SEM picture of as-grown sputtered ZnO.

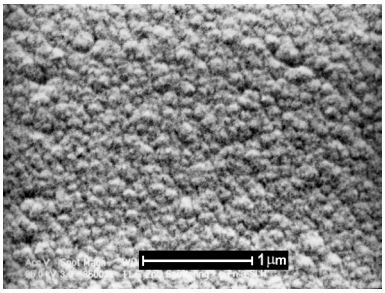

Fig. 4b: SEM picture of the surface of a p-i-n a-Si:H solar cell deposited on a as-grown sputtered ZnO.

Figs. 5a and 5b show SEM pictures of the post-etched sputtered ZnO layer (a) and the n-layer of the p-i-n solar cell deposited on it (b).

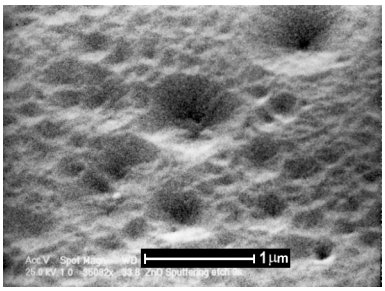

Fig. 5a: SEM picture of the surface of a sputtered ZnO post-etched with an HCl solution.

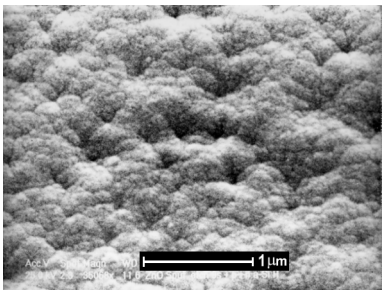

Fig. 5b: SEM picture of the surface of a p-i-n a-Si:H solar cell deposited on a sputtered post-etched ZnO.

Figs. 4 and 5 reveal that the a-Si:H cells reproduce relatively well the surface topology of the front ZnO itself with an additional fine sub-roughness. One can observe in Fig. 5b the same "holes" that were created by the post etching treatment of the front ZnO layer (Fig. 5a).

Figs. 6a and 6b show SEM pictures of the LPCVD ZnO layer (a) and the n-layer of the p-i-n solar cell deposited on this front ZnO (b). The bare LPCVD ZnO has a strong pyramidal surface topology which is quite different to the sputtered ZnO. The strong edged pyramidal ZnO surface is smoothed out by the covered a-Si:H cell (Fig. 6b).

Figs. 7a and 7b show SEM pictures of the post-etched LPCVD ZnO layer (a) and the p-i-n solar cell deposited on it (b).

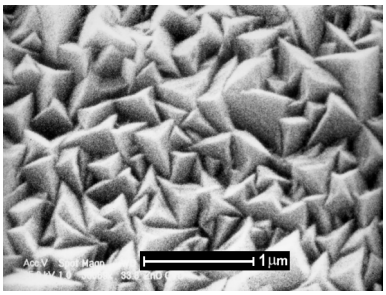

Fig. 6a: SEM picture of as-grown LPCVD ZnO surface.

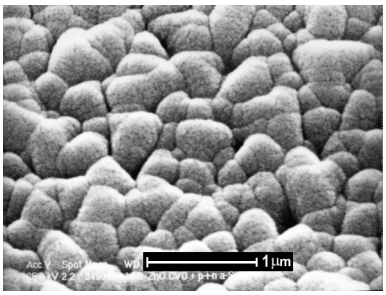

Fig. 6b: SEM picture of a p-i-n a-Si:H solar cell deposited on a LPCVD ZnO layer.

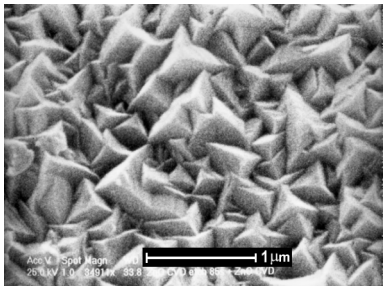

Fig. 7a: SEM picture of the surface of the LPCVD ZnO layer post-etched with an HCl solution and with an additional thin layer of LPCVD ZnO layer.

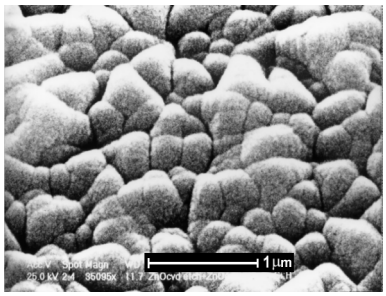

Fig. 7b: SEM picture of a p-i-n a-Si:H solar cell deposited on a LPCVD post-etched ZnO layer.

In contrast to sputtered ZnO, LPCVD ZnO keeps the surface topology after etching. However, it has to be noted that the haze and the RMS roughness are further increased by this additional etching step.

The strong different "character" between the surface topology of sputtered ZnO and LPCVD ZnO, in combination with the surface topology of the cells, may be a reason for the considerably enhanced SR of cells deposited on LPCVD ZnO (Figs. 2&3). Therefore, this indicates that the topology of the surface might be also an important parameter for the light trapping. Additional support comes from the fact that in case of our as-grown LPCVD ZnO and post-etched LPCVD ZnO the SR of the cells deposited on these ZnO layers are identical in spite of an increased haze.

4. CONCLUSIONS

Spectral response (SR) measurements were done for identical amorphous silicon solar cells deposited on four front ZnOs having each different haze factor values. An evident correlation between the variation of SR and the variation of haze factor could not be found.

These results indicate a difficulty in the prediction of the performance of amorphous silicon p-i-n solar cells when using the haze factor alone as criteria for the light trapping properties of the front TCO.

Our SEM observations suggest that beside the roughness and the haze factor the "character" of the topology of the front TCO and the related topology of the amorphous solar cell deposited onto this layer have probably to be taken into account to explain the light trapping potential in the cell. Unfortunately, our results do not identify which scattering interface (ZnO/cell or cell back side/ZnO) is more important for the light trapping. Further investigations are required to distinguish and identify the important interface for the enhancement of light trapping.

Finally, we suggest that further surface characterization of rough TCO layers should be investigated and compared with cell performances.

5. ACKNOWLEDGEMENT

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